The interaction between physical and sedimentary biogeochemical processes in south-west Spencer Gulf, South Australia.

Emlyn Morris Jones B. Sc. (Hons)

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Contents

Abstract

Located in the south-west region of Spencer Gulf, South Australia, a multi-million dollar aquaculture industry based on the ranching of southern bluefin tuna (*Thunnus maccoyii*) contributes significantly to the regional economy. The interaction between aquaculture activities and the environment is of significant interest to industry stakeholders, management authorities and the broader science community. No studies, to the best of my knowledge, have investigated the relationships between the hydrodynamics and biogeochemistry of the system and the ability of the benthic ecosystem to deal with the increased loads of organic material from aquaculture activities. This thesis uses a multi-disciplinary approach combined with modern statistical techniques to explore the linkages between hydrodynamics, sediment geochemistry, sedimentary nutrient cycling and the aquaculture industry.

Modelling results have identified that swell entering the mouth of Spencer Gulf from directly south causes the greatest swell heights in the central tuna farming zone. Winds from the north-east through to south-east generate the greatest wind-wave heights in the central tuna farming zone. This is directly related to the available fetch. The energy

contained in the locally generated wind waves was the same order of magnitude as that of the dissipated oceanic swells. Yet the incoming swell poses the greatest risk to aquaculture activities as the increased wave length causes swell energy to penetrate to the seafloor.

The results of this work suggest that the sediment geochemistry is tightly coupled to both the hydrodynamic regime and the buildup of silt originating from aquaculture activities. In the more exposed regions of the tuna farming zone, periodic resuspension events caused by swell propagating into the area from the Southern Ocean, resuspend fine unconsolidated sediments into the lower 10 m of the water column. This material is then advected through the region by the residual (low-frequency) currents until it settles out in areas of lower energy. This process has created two distinct provinces within the region that can either be classified as depositional or erosional.

The combined effect of wave action and tidal currents have generated a heterogeneous distribution of biogeochemical properties within the sediments. Denitrification rates were measured in these heterogeneous sediments using a novel technique based on Bayesian statistics to explicitly account for the spatial variability of the sediment biogeochemistry. The denitrification rates were found to be generally low, largely due to the lack of organic matter entering the sediments. However, adjacent to aquaculture activities, the high organic loads stimulate sedimentary denitrification, with rates reaching values of up to three orders of magnitude greater than the control sites. Denitrification efficiencies were high adjacent to the aquaculture activities, with up to

95% of the dissolved inorganic nitrogen produced from the breakdown of organic matter in the sediments being removed. Variability in the denitrifcation efficiencies was related to the textural characteristics of the sediments, with high efficiencies in finer sediments. It is proposed that this is due to the lower permeability of these sediments restricting the advective exchange of porewater nutrients.

Declaration

I certify that this thesis does not incorporate, without acknowledgment, any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Emlyn Jones

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Chapter 1

General introduction

The 3000 km southern coastline of Australia extends from Cape Leeuwin in the west to South-East Cape in Tasmania (Figure 1.1). Along sections of the shelf, strong upwelling during the months of January to April brings cool nutrient-rich water into the photic zone (Middleton & Bye, 2007), enhancing primary productivity in an otherwise oligotrophic ocean. This primary productivity supports vast schools of sardines (McClatchie *et al.* , 2007), which in turn are targeted by predators such as southern bluefin tuna (*Thunnus maccoyii* hereafter referred to as SBT), in higher trophic levels. Over 95% of Australia's quota of SBT are caught along the continental shelf of central South Australia. In response to the reduction of the SBT quota in the early 1990's a value-adding process, whereby the SBT are fattened over a 6 month period, has been adopted by the industry. The SBT are caught near the shelf break in the eastern Great Australian Bight, then towed to south-west Spencer Gulf (Figure 1.2). The SBT are then transferred to pontoons (Figure 1.3) in the tuna farming zone (TFZ), where they are fattened and then harvested for export, often to Japan. The interaction between the aquaculture activities and the environment in the TFZ are of considerable interest to the tuna industry and management authorities.

Prior to 1996 the TFZ was mostly located within the sheltered Boston Bay, adjacent to Port Lincoln. In April of 1996, a severe weather event caused a widespread sediment resuspension episode which led to the mortality of up to 75% of fish (Clarke, 1996). Subsequently the TFZ was fully relocated to the more exposed region to the east of Boston Island, where it is thought that the more energetic conditions will decrease the amount of waste material deposited under the tuna pontoons. This chapter describes the regional setting of this area, introduces previous research and presents the aims and objectives of this thesis.

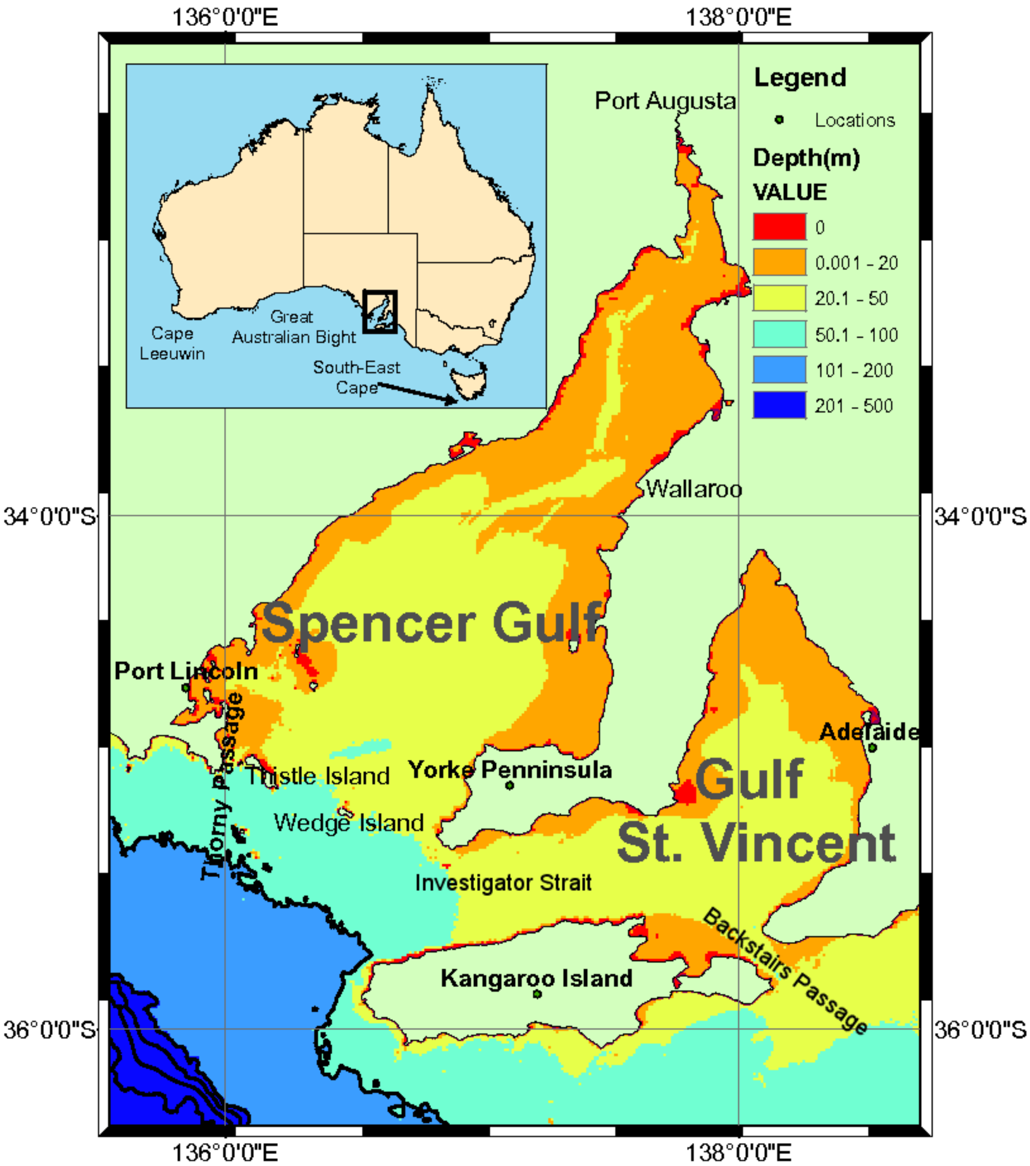

Figure 1.1: The central South Australian coastline depicting the major features of Spencer Gulf, Gulf St Vincent and Kangaroo Island.

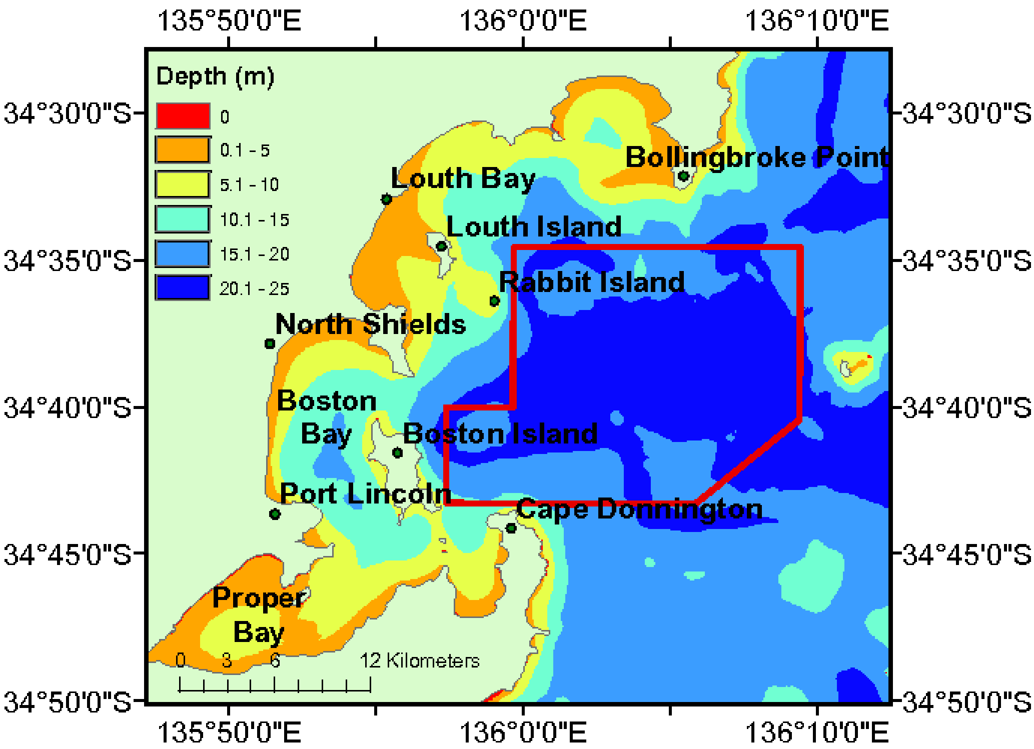

Figure 1.2: The south-west region of Spencer Gulf with the post 1996 tuna farming zone denoted with the red border.

Figure 1.3: A pontoon used for the farming of southern bluefin tuna.

1.1 Regional setting

1.1.1 Bathymetry

The dominant features of the central South Australian coastline are Gulf St Vincent, Spencer Gulf and Kangaroo Island (Figure 1.1). The southern entrance to Spencer Gulf contains a number of small islands on its western side, including Thistle Island and a small group in the centre dominated by Wedge Island. Kangaroo Island lies directly south of Gulf St Vincent and is separated from the mainland by two passages of water, Investigator Strait and Backstairs Passage. Most of the coastlines in the region are low and rocky, consisting of limestone and carbonate sediments. The continental shelf extends some 80-200 km south of the mainland and Kangaroo Island to the shelf break where it abruptly drops to the abyssal plain at 4000 m depth. Several submarine canyons bisect the shelf break to the south of Kangaroo Island. These canyons have recently been the subject of process studies and surveys with regard to their role in upwelling events and the supply of nutrients to shelf waters (McClatchie *et al.* , 2006; Kämpf, 2007).

1.1.2 Physical oceanography

Within this region the physical oceanography has been of great interest in recent years. The shelf circulation is complex with the Flinders current following the shelf break at depths of between 200 - 500 m (Middleton & Bye, 2007). The influence of synoptic weather patterns generates coastally-trapped waves which propagate to the east, particularly in the summer months. It is unclear if and how these waves modify the circulation in the Gulfs (Middleton & Bye, 2007). As suggested by Kämpf (2007) the presence of shelf break canyons may aid in the transport of cool deep nutrient-rich water on to the shelf. This, in conjunction with the well understood Ekman generated upwelling, suggests the presence of a pool of cold, nutrient-rich water that resides on the shelf west of Kangaroo Island, persisting through the summer months (McClatchie *et al.* , 2006).

Historically, Spencer Gulf has been studied in detail and the circulation has been described by a number of authors (Noye, 1984; Nunes & Lennon, 1986; Lennon *et al.* , 1987; Petrusevics, 1993). There is agreement that Spencer Gulf is an inverse estuary whereby the salinity increases towards the north. Furthermore, it has been suggested by Lennon *et al.* (1987), and confirmed with satellite imagery (Petrusevics, 1993), that due to heating in summer a density front establishes across the mouth of the Gulf. This front limits the exchange between Gulf and oceanic waters. Recent evidence suggests that some of the upwelled water may actually cross the density front in the lower layers, occasionally reaching the TFZ (Herzfeld *et al.* , 2009). During winter, a gravity current forms and flows down the eastern side of Spencer Gulf spilling on to the shelf and down the du Couedic canyon on the shelf break (Lennon *et al.* , 1987) (Figure 1.4).

The circulation within Spencer Gulf can be divided into two distinct regions; the southern region, extending from the entrance up to Wallaroo, and the northern region from Wallaroo to the head of the Gulf near Port Augusta. The southern region exhibits weak residual clockwise circulation which is a result of the local wind forcing (Herzfeld *et al.* , 2009). During

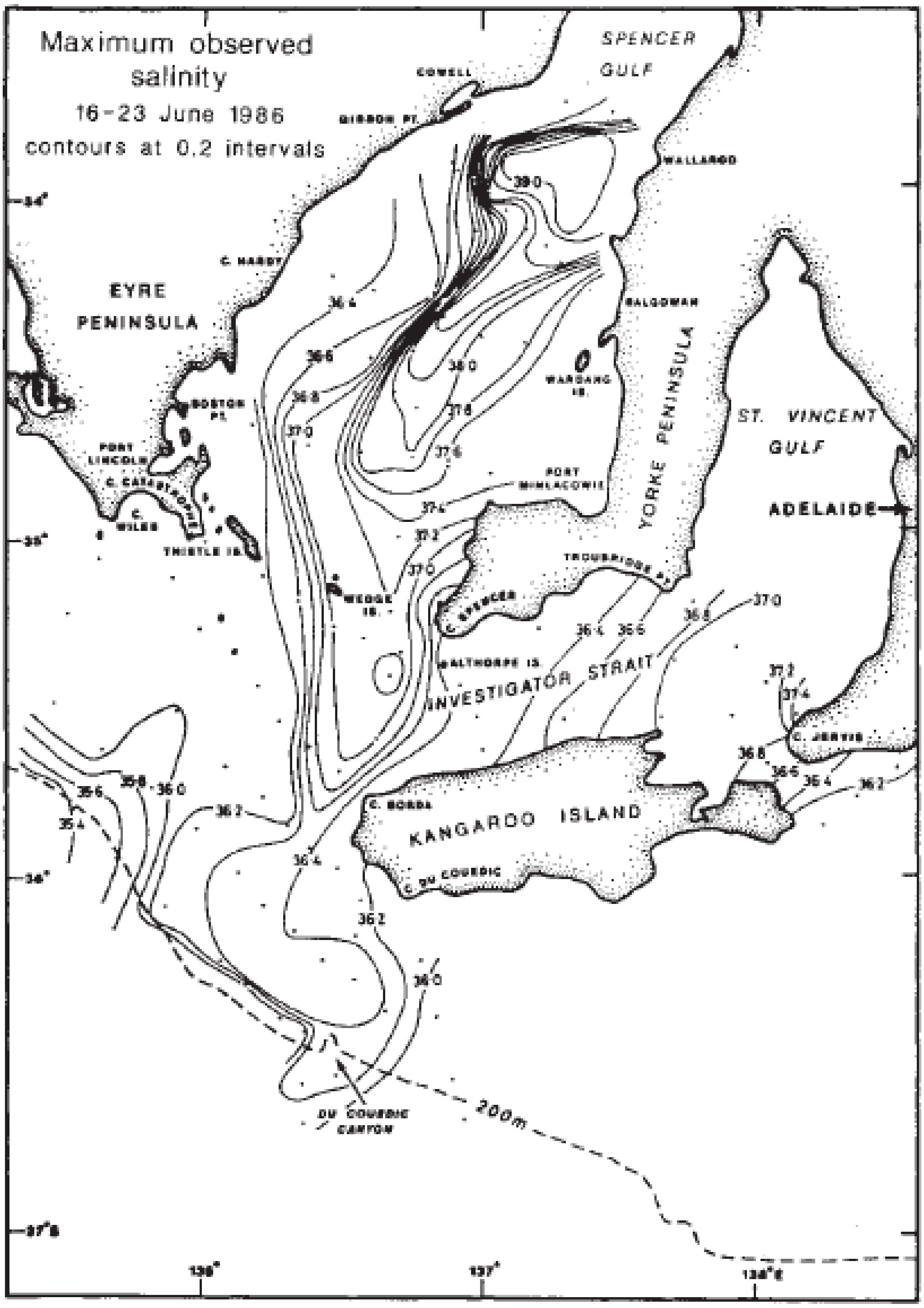

Figure 1.4: A salinity contour map depicting the location of the dense gravity current formed during the Austral winter (Lennon *et al.* , 1987).

summer the evaporation rates in the northern region produce a warm salty watermass that remains isolated from the southern region. During autumn, this water mass cools and trickles down the eastern side of the Gulf and can be seen in many conductivity, temperature and depth (CTD) observations as a cold, salty water mass (Lennon *et al.* , 1987). It is this thermohaline exchange that forces the flushing of northern Spencer Gulf (Kämpf *et al.* , 2009). Monthly averaged temperature-salinity diagrams for various stations in the Gulf clearly display the seasonal flushing signature (Figure 1.5).

The tidal regime of Spencer Gulf is unusual. The tidal elevations are < 2 m in the southern section of the Gulf, leading to it being classified as micro-tidal in nature. The tidal elevation increases towards the head of the Gulf due to tidal resonance. Port Augusta at the head of the Gulf experiences 3-4 m tides and is on the verge of being classified as macro-tidal. Its most unusual feature is that it experiences the 'dodge' tide. This is a phenomena whereby the diurnal and semi diurnal tidal constituents are of the same magnitude and when there is a 180 degree phase difference, the combined effect of the signals cancel each other out and cause little if any tidal movement over the 12 hour cycle. This dodge tide occurs every lunar cycle. The dodge tide can have a profound effect on the biology of the region; due to lack of tidal movement, the dissolved oxygen (DO) drops to near anoxic levels in some regions.

Initial attempts at modelling the hydrodynamic regime of the TFZ are contained in Grzechnik (2000), with more recent high resolution 3-D modelling reported in Herzfeld *et al.* (2009). Typical flushing times for the TFZ are approximately 2 days, whereas in the more sheltered Boston and Proper

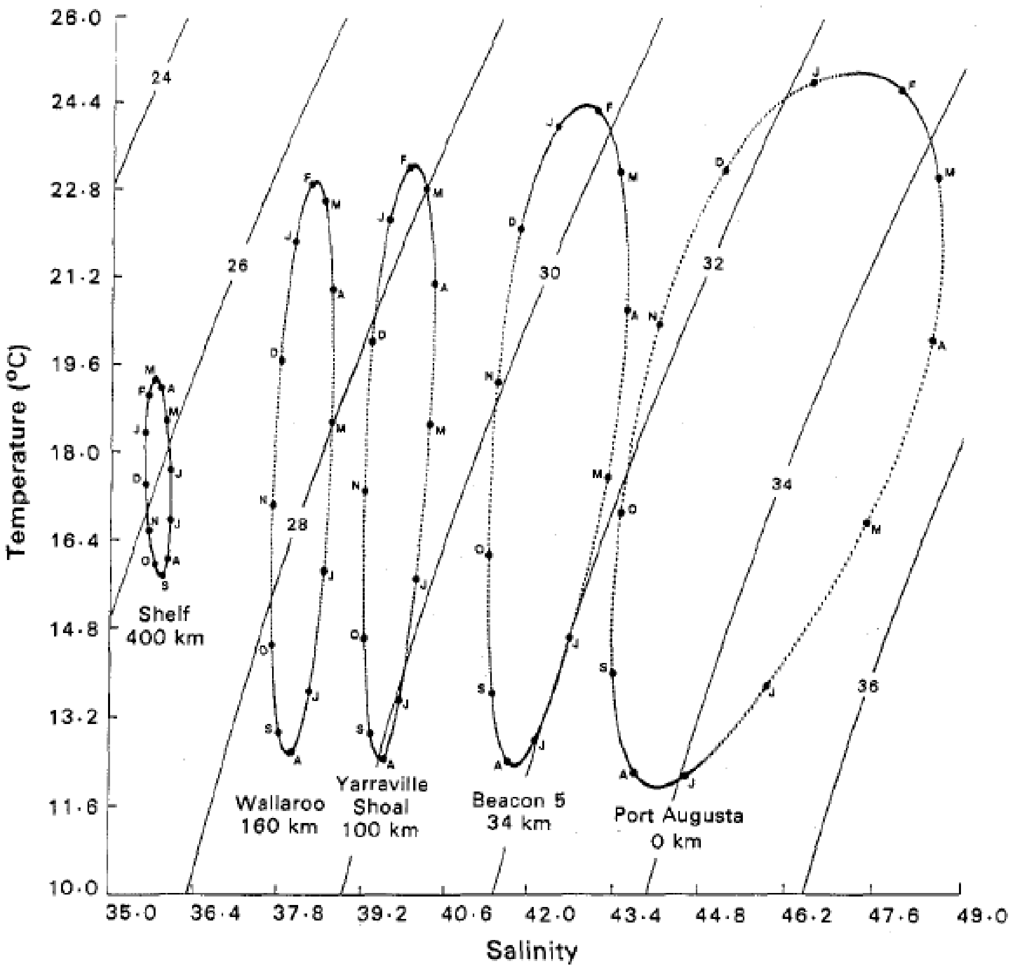

Figure 1.5: The seasonal temperature and salinity cycles at various locations in Spencer Gulf. Due to negligible riverine inflow, changes in salinity are caused by exchange with fresher oceanic water (Nunes & Lennon, 1986).

Bays, the flushing times are longer and are of the order of 8-10 days. The tidal currents in this part of the Gulf are reasonably strong and reach a maximum speed of around 20 cm s^{-1}, which have the ability to generate displacements of particles of up to 8 km in a tidal cycle. In contrast to the tidal currents, the observed and modelled residual circulation is weak, with typical speeds in the order of 1 cm s^{-1}. The combined effect of the tidal and residual flow creates distinct subregions having limited connectivity (Figure 1.6). The exchange between the coastal regions and the TFZ is enhanced during summer in response to local upwelling generated by easterly winds.

Very few studies have investigated the wave regime of the gulfs of South Australia. The swell climate of Spencer Gulf was first mentioned in Noye (1984), who presented results detailing the persistence of oceanic swell along the north-south axis of Spencer Gulf. The first wave-modelling study of this region was conducted by Hemer & Bye (1999), who investigated the attenuation of oceanic swell over the continental shelf and who empirically fitted equations predicting swell height at various coastal locations using the oceanic swell height, period and direction at the shelf break. The first study to investigate the combined effects of swell and wind waves was that of Pattiaratchi *et al.* (2007), which was confined to Gulf St Vincent.

1.1.3 Sediments

Recent 3-D sediment modelling studies of this region are contained in Margvelashvili (2009) and are forced with the output of the wave model from Chapter 2 of this thesis. The findings of Margvelashvili (2009) suggest that fine sedi-

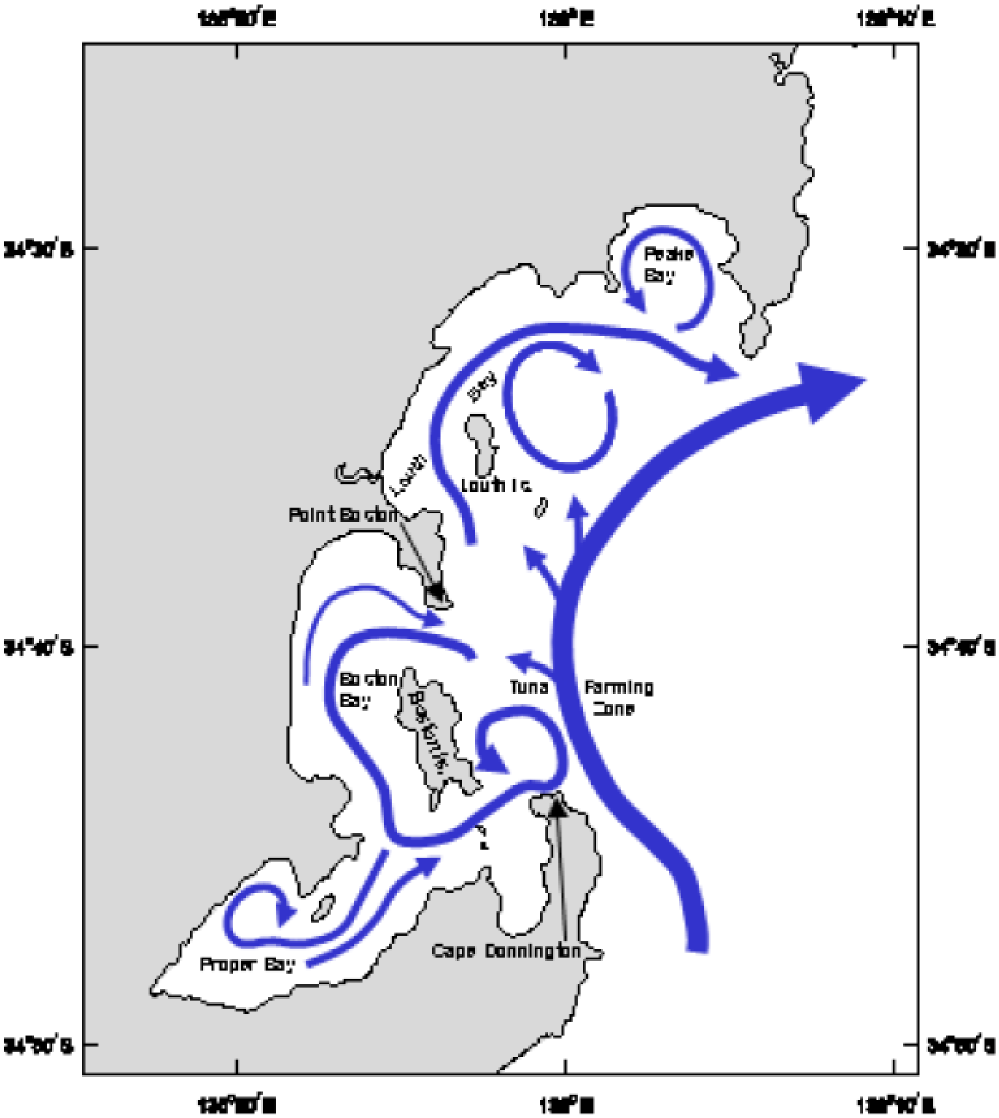

Figure 1.6: The mean depth integrated currents in the TFZ (Herzfeld *et al.* , 2009).

ments are resuspended regularly and are derived from fresh sediment deposits or unconsolidated layers. The probability of sediment resuspension on the western side of Boston Island and in Proper Bay is the lowest in the model domain. The model also suggests the potential for unconsolidated sediments in the central region of the TFZ to be resuspended (Figure 1.7).

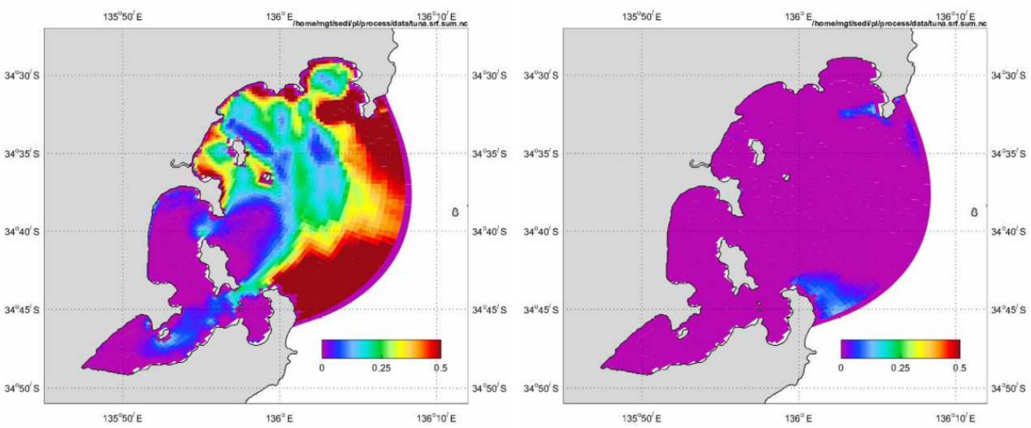

Figure 1.7: The simulated probability of sediments becoming resuspended for a critical friction velocity of 0.014 m s^{-1} (left) and for a critical friction velocity of 0.005 m s^{-1} (right) (Margvelashvili, 2009).

Since the 1996 tuna mortality event, there has been significant interest in defining the regional sediment types in SW Spencer Gulf. The sediments in this region are discussed in Fernandes *et al.* (2006), and are a mixture of sediments found on the shelf and those further north. The sediment type on the adjacent continental shelf is dominated by calcareous sediments from the erosion of carbonate deposits (Harris, 1994). Sediment transport on the shelf is dominated by wave-induced transport as a result of storm activity; this transitions to tidally-induced sediment transport in Spencer Gulf (Porter-Smith *et al.* , 2004). Observations presented in Fernandes *et al.* (2006) suggest that in SW Spencer Gulf a mixture of the two processes causes the winnowing out of fine sediment fractions at more exposed locations; this is supported by the findings of Margvelashvili (2009).

1.2 Aquaculture

Throughout the world, there has been an ever increasing demand for seafood. As a direct result of this increasing demand and declining wild fish stocks, aquaculture has grown dramatically. Aquaculture practices vary widely depending on the geographic location and demand for various fish species. In North America, Northern Europe, New Zealand and Tasmania salmonid farming using pellet feeds is common. Within these regions the interaction between the aquaculture activities and the environment differs due to regional environmental characteristics. Typically, environmental impacts arise from high organic and nutrient loadings derived from uneaten feed and excreted waste from the farmed species (Wu, 1995). If the inherent hydrodynamics do not disperse the waste, the accumulation of organic matter on the seafloor can lead to changes in benthic communities (Vita & Marin, 2007). In extreme cases, it has been found that the high nutrient loads can lead to eutrophication, similar to that caused by other anthropogenic activities. Such events have resulted in harmful algae blooms causing the mass fatalities of farmed fish (Diego-McGlone *et al.* , 2008). Kalantzi & Karakassis (2006) have reviewed the issues of benthic impacts from marine fish farming and found that depth, distance from pontoon and latitude of aquaculture site, were the best predictors of sediment geochemistry.

Within Australia, there are three major finfish aquaculture regions; the

Huon-D'Entrecastuex Channel and Macquarie Harbour in Tasmania and Spencer Gulf in South Australia. Previous studies in the Huon-D'Entrecasteaux Channel have used a combination of field studies and biogeochemical (BGC) modelling to investigate the interaction between aquaculture and the environment (Wild-Allen *et al.* , 2004). BGC modelling can be used as a tool to simulate various scenarios accounting for variations in environmental forcings or increased/decreased nutrient loads from point sources. These studies have played an important role in informing management authorities on how aquaculture activities should be managed and potential carrying capacities of the aquaculture zones.

Research in the TFZ in SW Spencer Gulf has previously examined the effects of aquaculture on the seafloor (Lauer, 2005), finding that aquaculture activities significantly stimulated benthic metabolism. Nutrient fluxes from the sediments were found to follow a distinct seasonal cycle that coincides with the tuna farming season. A conceptual model of the nitrogen metabolism of SBT found that approximately 7 -18 % of the nitrogen that enters the system from tuna feed is deposited on the seafloor as particulate organic nitrogen (PON) (Figure 1.8)(Fernandes *et al.* , 2007b). Less than half of this PON is stored in the sediments while the remaining fraction diffuses into the water column. It is unclear from previous studies how much nitrogen is removed from the system through the process of denitrification.

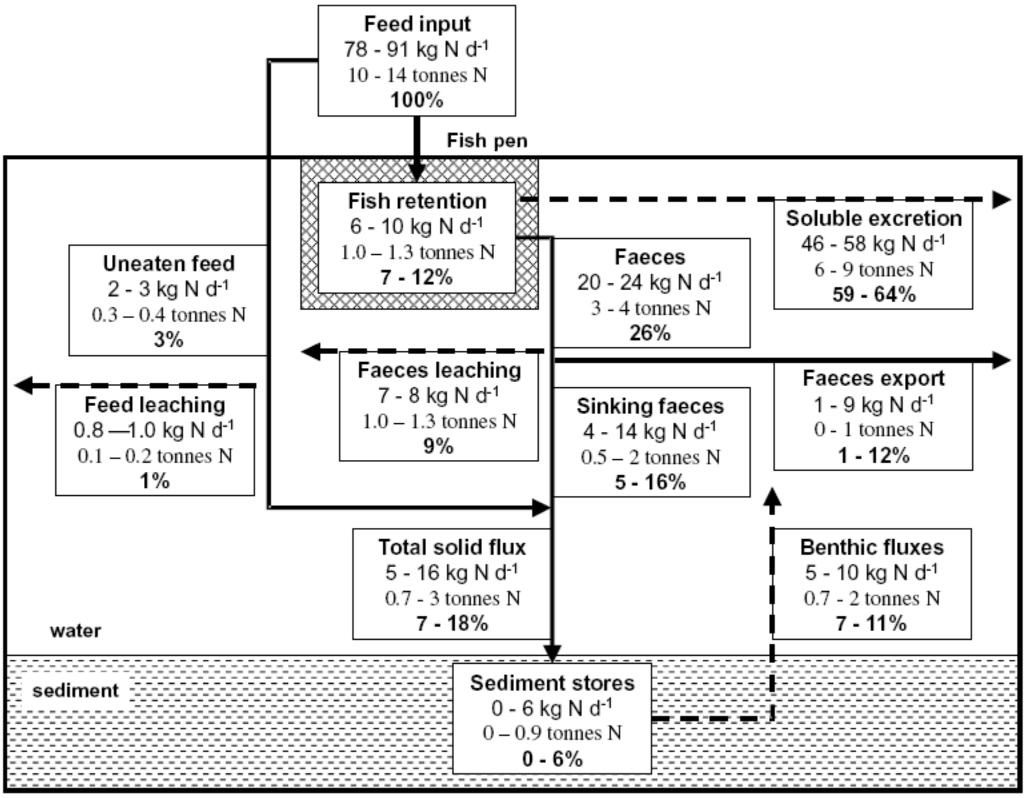

Figure 1.8: A conceptual model of the environmental flow of nitrogen entering a tuna pontoon with tuna feed (Fernandes *et al.* , 2007b).

1.3 Nutrient cycling and benthic metabolism

Nitrogen in the coastal marine ecosystem (Figure 1.9) is often thought of as the major limiting nutrient that controls primary productivity being cycled through a number of different and often complex pathways (Hecky & Kilham, 1988; Herbert, 1999). Nitrogen, in the form of Dissolved Inorganic Nitrogen (DIN), comprising of nitrite (NO_2^-), nitrate (NO_3^-) and ammonia (NH_4^+), are the most readily bioavailable forms of nitrogen. DIN can either be advected into a coastal region or other forms of nitrogen can be transformed into DIN locally. Within coastal marine ecosystems, the advective flux of DIN can be derived from the lateral advection of nutrient rich water through the process of upwelling. Local fluxes can be derived from river input, anthropogenic sources such as effluent discharge, aquaculture activities or through ecosystem transformations such as mineralisation, nitrogen fixation, nitrification to name a few (Figure 1.10). Removal of DIN from coastal ecosystems may occur via similar pathways. Nutrient rich waters can be advected and subjected to downwelling, and there can be losses of DIN through microbial processes.

A major pathway through which DIN is lost from the benthic ecosystem is through the process of sedimentary denitrification. Denitrification transforms nitrate into N_2 gas, at which point nitrogen is no longer considered a biologically available. The process of sedimentary denitrification is tightly linked to the microbial community. In coastal environments most denitrification takes place in the anoxic zone of the sediments. Where regions experience strong tidal flows or oscillatory motion associated with surface gravity waves, there is often substantial spatial variation in microbial communities

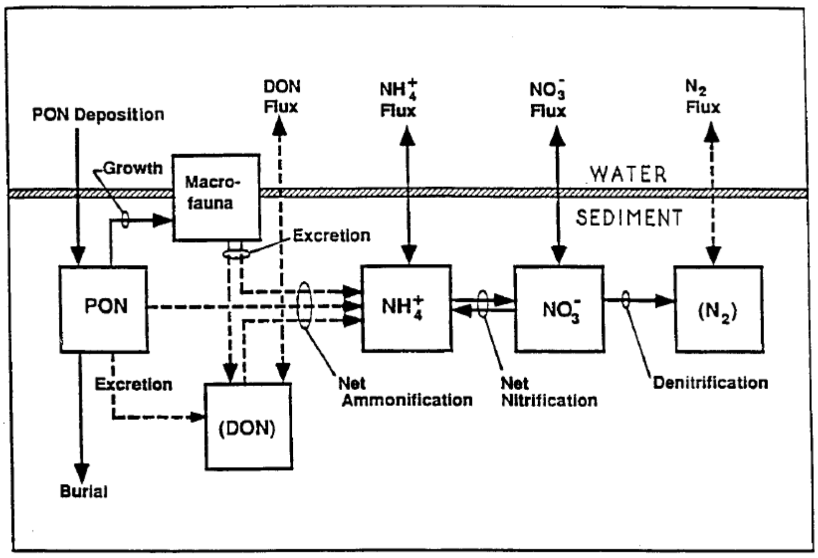

Figure 1.9: The idealised marine nitrogen cycle (Kemp *et al.* , 1990).

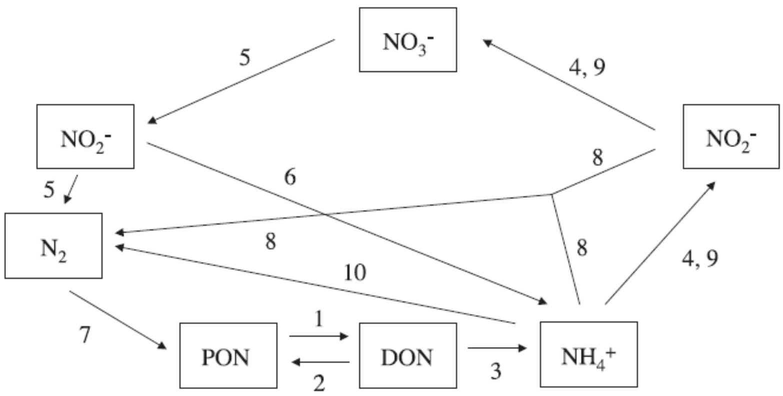

Figure 1.10: A schematic diagram detailing the processes responsible for transformation amongst various species of nitrogen present in the marine environment. Hydrolysis of organic polymers (1), biological incorporation (2), ammonification (3), nitrification (4), denitrification (5), dissimilatory nitrate/nitrite reduction to ammonium (DNRA) (6), nitrogen fixation (7), anaerobic ammonium oxidation by nitrite (Anammox) (8), and anaerobic ammonium oxidation to nitrite and nitrate (9) or N_2 (10) (Hulth *et al.* , 2005).

over very short length scales (Cardenas *et al.* , 2008).

1.4 Aims of this thesis

In this thesis the interaction between the physical environment and the biogeochemistry of the sediments is investigated using a multidisciplinary approach. The goals of this thesis are:

- To determined the combined swell and wind wave regime of south-west Spencer Gulf using a combination of in situ and remotely sensed observations and numerical modelling using SWAN.
- To investigate the interaction between the wave regime of south-west Spencer Gulf and the sediment dynamics, including sediment resuspension the transport of sediments in the TFZ. A combination of modelling, observations and theoretical sediment dynamics are applied.
- Using the wave modelling results and observed sediment distributions, a sea-floor classification is developed and its relationship with aquaculture activities is explored?
- The *in situ* denitrification rates and related spatio-temporal variability is explored using a new, innovative statistical technique, the implications of these findings are then discussed in the context of the regional aquaculture industry.

1.4.1 Structure

The thesis is structured such that each Chapter is a paper or at the very least can be read as a standalone document. Inevitably there will be some repetition in the Introductions to the Chapters, which is unavoidable given the structure. The thesis is divided into two parts:

- Part 1: The physical oceanography of south-west Spencer Gulf,
- Part 2: The sediment biogeochemistry of south-west Spencer Gulf.

Part 1 is divided into two chapters based on field studies and numerical modelling: the first is a detailed investigation into the combined swell and wind wave regime of the area, while the second examines the relationship between waves, sediment resuspension and the textural characteristics of the sediments.

Part 2 contains a further three chapters investigating small and large scale spatial variations in sediment geochemistry and denitrification. These distributions and processes are then related back to the physical conditions and anthropogenic inputs to this area.

This is the first detailed study that has investigated the interactions between the physical forcings, anthropogenic inputs through aquaculture and sediment biogeochemistry within south-west Spencer Gulf and to the best of my knowledge in any temperate oligotrophic region.